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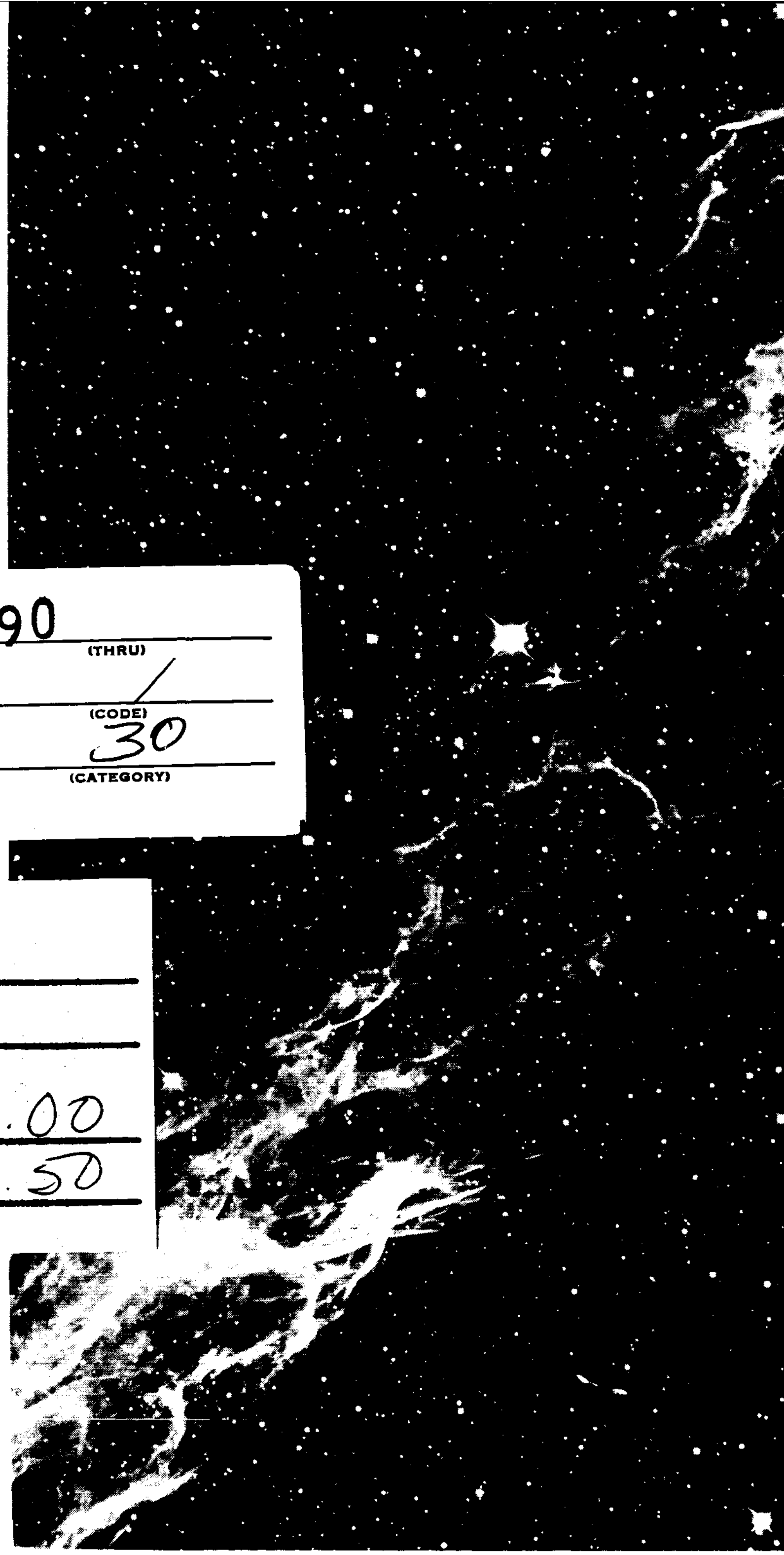

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THE SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS - SATURN, URANUS, NEPTUNE AND PLUTO

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THE SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS - SATURN, URANUS, NEPTUNE AND PLUTO

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SUMMARY

This document reports a study performed by the Astro Sciences Center of IIT Research Institute on the scientific objectives for the four outermost planets: Saturn, Uranus, Neptune, and Pluto. Jupiter, often included in descriptions of outer planets, has been treated independently (Roberts 1964) and so is not discussed in detail at this time.

The four outermost planets, with the possible exception of Pluto, differ radically in many respects from those nearer the Sun. The differences are shown in this report in a general survey of the structure and composition of these planets and in more detailed discussions of the individual bodies. It is seen that models for the planetary interiors are necessarily rather incomplete at the present time, while descriptions of the atmospheres have been carried somewhat further along, primarily with the aid of spectroscopic and radiometric observations. Some of the better known characteristics are included in the table at the end of the summary. Much of the data is only qualitative at this time, however, so that the potential for experimental investigations using space probes is very great.

In particular, missions to these planets will allow the species concentration and distribution within the

atmosphere to be tentatively established. Observations can determine the ammonia content of the Saturn atmosphere and also yield a value for the hydrogen-helium ratio on Uranus and Neptune. Such information, along with temperature measurements, will provide for an understanding of the energy balance throughout the atmospheres and, to a lesser extent, within the bodies of the planets. The magnitude and configuration of the planetary magnetic fields will also represent significant new knowledge, as will the determination of the presence or absence of ionospheric and auroral effects.

Observations from a spacecraft could further provide some understanding of the belts, spots, zones, and other features which have been observed on Saturn. The origin of the nonthermal radio noise from this planet might be explained. It may also be possible to determine the exact nature of the particles in the ring system.

Since Uranus and Neptune are very far from Earth, there does not yet exist much detailed information of atmospheric features or content. Thus many things would be measured for the first time. One such important determination would be the mean molecular weight of their atmospheres. As for Pluto, so few facts are known that just the determination of its mass and diameter would represent meaningful experiments.

The measurements which are proposed are: 1) magnetic field measurements throughout the mission and in the region of the planets, 2) spectrometry and polarimetry of the planetary atmospheres, 3) microwave radiometry and radar probing, 4) charged particle detection in trapped radiation belts, 5) optical occultation experiments for Saturn's ring system and atmospheric studies, 6) RF occultation experiments for atmospheric density determinations, and 7) photography of cloud structure and, where possible, surface features of the planets.

SUMMARY OF PHYSICAL PROPERTIES

Planet	Atmosphere Known Constituents and Estimated Temperature	Interior Principal Constituents	Additional Features of Interest
Saturn	Ammonia, methane, and hydrogen 90°K-100°K	Primarily hydrogen and helium	Has the only satellite (Titan) on which an atmosphere has been observed
Uranus	Methane, hydrogen 70°K-80°K	Ammonia, methane, and water	Axis of rotation lies practically in ecliptic plane.
Neptune	Methane, hydrogen $T \approx 70$°K	Ammonia, methane, and water	Has large satellite (Triton) which is in retrograde motion.
Pluto			Estimate of diameter ($\approx$ 6000 km) is the only physical data for this planet.

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1. INTRODUCTION

The major planets Jupiter, Saturn, Uranus, and Neptune and the distant planet Pluto lie beyond the asteroid belt. Although this study is properly concerned with the four outermost planets, and although Jupiter has already been studied extensively (Roberts 1964; Witting, Cann and Owen 1965), some mention will be made of this latter body in the following discussion because of its similarity to the other major planets and because certain assumptions can be made based on the greater knowledge of Jupiter. Conversely, because of Pluto's great distance and because of the paucity of data concerning its characteristics, only a limited discussion of this planet can be given at this time.

The major planets are large (50 to 140 thousand kilometers in diameter), low density (0.7 to 2.5 gm/cm^3) bodies with extensive, optically thick atmospheres whose principal constituents include hydrogen (H_2), helium (He), methane (CH_4), and ammonia (NH_3) in varying amounts. One of the primary constraints upon any theory of the origin of the solar system is the necessity of logically explaining the differences between these major planets and the more familiar terrestrial planets. Certain work in the past, due largely to Rabe (1956), strongly implies that Jupiter was once significantly more massive than it is now. Further, the protoplanet theory of Kuiper (1956b) the most generally satisfactory theory available today for the origin of at least the major planets, indicates that all of the major planets were once more massive than now and that they were originally of solar composition. Rabe (1958) has shown that such a solar system could be stable and not essentially different in orbital elements from the system of today. Most of the differences between the major planets can be explained at least qualitatively within the framework of these assumptions. However, attempts to include the terrestrial planets have been generally objected to by Urey, and certainly the detailed mechanism in the inner part of the solar system was different (Newburn 1961).

Considered individually, the nearest of the four outermost planets, Saturn, is probably the most interesting object to be seen through a telescope. Lightly shaded surface bands, more uniform than those of Jupiter, parallel the rings. Occasionally, detailed markings can be distinguished which reveal the rapid turning of the planet. The ring itself is divided into three major divisions, a bright middle ring, a fainter outer ring, and a barely luminous "crape" or inner ring. The two outer rings are broken by narrow dark gaps detectable only under ideal conditions. In addition, Saturn has a system of nine satellites, five of which have been determined to have a density less than 2.4.

Uranus and Neptune, the "twins", have diameters about four times that of the Earth. Uranus is somewhat the larger, but the measures are uncertain because of the hazy edges of the disks. Although features are difficult to observe on Neptune and only faint characteristics have been seen on Uranus, the planets are certainly enveloped with atmospheres resembling those of Jupiter and Saturn. Because of their great distance from the Sun, however, temperatures are very low so that some constituents are frozen out and therefore not readily detectable.

Since certain comparisons will be made later based on quantitative values for various parameters, Table 1 gives, at this point, the principal physical data in use at present for the four outer planets. Certain additional features should also be mentioned here.

Spectroscopic observations have shown that Saturn's rotation period increases steadily toward higher latitudes, and is fully an hour longer at latitude 57° than at the equator. Compared with the rotation at latitude 36° as standard, there is an eastward current along the equator with a velocity of some 400 meters/sec (Whipple 1963). As in the case of Jupiter,

Table 1

PLANETARY CONSTANTS*

Property	Earth	Saturn	Uranus	Neptune	Pluto
Semi-major axis of orbit, AU	1.000	9.540	19.18	30.07	39.44
Sidereal period, tropical years	1.00004	29.45772	84.013	164.79	248.4
Eccentricity	0.016771	0.056063	0.0471	0.008[illegible]	0.2494
Inclination to ecliptic	0°00'00.0"	2°29'26.1"	0°46'22.5"	1°46'28"	17°10'
Radius (equatorial), kilometers	6378	60,400	23,800	22,200	
Earth = 1	1.00	9.47	3.73	3.49	
Mass, Earth = 1	1.0	95.2	14.5	17.2	
Density, g/cm^3	5.52	0.684	1.60	2.25	
Rotation period (equatorial)	$23^h56^m4.1^s$	10^h14^m **	10^h49^m	15^h	6.39^d
Inclination of equator to orbit	23°27'	26°44'	97°55'	28°48'	
Oblateness, $(R_e-R_p)/R_e$	0.0034	0.096	0.06	0.02	
Attractive surface gravity, cm/sec^2	982	1120	940	1500	
Albedo	0.40	0.57	0.80	0.71	
Escape velocity, km/sec	11.2	37	22	25	
Atmospheric constituents (observed)		NH_3, CH_4, H_2	CH_4, H_2	CH_4, H_2	
Atmospheric temperature (spectroscopic estimates in °K)		90-100	70-80	70	
Number of satellites	1	9	5	2	

* All data from Allen (1963)

**10^h38^m for temperate zones

Earth mass = 5.977×10^{27}g

the edges of Saturn's disk are much less brilliant than the center. The belts are also less sharply defined and less variable. There is usually a brilliant yellow zone at the equator, and a dark cap of greenish hue at the pole. When the ring is invisible, the planet's light shows a small change with phase, which indicates that its reflecting surface is effectively smooth. When a large part of the light comes from the rings, however, much greater variation with phase is shown, which was one of the first arguments for the particulate constitution of the rings.

Not many detailed features are yet known about the twins, Uranus and Neptune. The high albedo of Uranus suggests that the visible surface is covered with clouds, and the heavy bands in the spectrum that the atmosphere is dense and extensive. Neptune shows no markings, but exhibits spectroscopic evidence of having an extensive atmosphere.

Very few facts are known about the planet, Pluto, except for its orbital characteristics. It appears faint and small with a color similar to that of the moon. It is thought by many to be similar in constitution to the familiar inner terrestrial planets.

In view of the paucity of information, it is exceedingly difficult to estimate the magnetic fields of these planets. Two planets are presently known to possess magnetic fields, Earth ($B_{surf} \cong 1/2$ gauss) and Jupiter ($B_{surf} \sim 10$ gauss), the value for Jupiter being quite uncertain. Both Jupiter and

Earth are fairly large, have relatively rapid rotation rates, and probably possess electrically conductive cores. Saturn, Uranus, and Neptune also possess these properties, and all lie between Earth and Jupiter in size. Therefore, in the absence of any more detailed information, it is reasonable to assume that their surface fields lie between 0.5 and 10 gauss, with Saturn's field somewhat larger than that of Uranus or Neptune.

2. GENERAL KNOWLEDGE OF THE OUTERMOST PLANETS

2.1 Characteristics as Related to the Solar System

The planets, in general, appear to form three chemically distinct groups. Group I consists of the terrestrial planets, of which the Earth is both the densest and the most massive. The planets of Group II, Uranus and Neptune, are more than ten times as massive as the Earth, but they are less than half as dense. Group III, made up of Jupiter and Saturn, are of the order of a hundred times as massive as the Earth and of very low mean density. Thus planets in the different groups differ widely in mass and the more massive planets contain much higher proportions of the lighter elements (see Table 2).

The cosmogonical significance of this grouping of the planets is somewhat clarified by Brown (1950), Ramsey (1951), and Wildt (1947). When the temperature is sufficiently low to permit the formation of molecules, the principal constituents of solar material fall into three well-defined classes. Class I consists of the common terrestrial materials, the most important being metallic iron and the oxides of iron, magnesium and

Table 2

PLANET GROUPS

Group	Principal Constituents	Comments
Group I Terrestrial planets	Class I materials; iron, oxides of iron, magnesium, and silicon	Relatively high mean atomic weight ($\geqslant 20$)
Group II Uranus and Neptune	Class II materials; water, methane, and ammonia	These planets are approximately ten times as massive as Earth. Only tentative atmospheric data exist. Mean atomic weight ≈ 4.
Group III Saturn and Jupiter	Class III materials; hydrogen and helium	These planets are approximately 100 times as massive as Earth. Contain large amounts of hydrogen; mean atomic weight ≈ 1.

silicon. These materials have high molecular weights and very high boiling points. The compounds of the second class have molecular weights ranging from 16 to about 20 and boiling points of the order of 100°K; the principal constituents in this class are water, methane, and ammonia. The third class consists of hydrogen and helium, which have the lowest molecular weights and also the lowest boiling points.

This separation of the constituents of solar material into three well-defined classes affords a possible explanation for the division of the planets into three chemically distinct groups. The terrestrial planets have been unable to retain the light volatile compounds of the second and third classes. The major planets, on the other hand, have retained large quantities of these materials. Such retention or loss of materials by planets is in general a strong function of the exospheric temperature. Specifically, heavier and cooler planets can retain light gases more easily than can the lighter and warmer planets. The fact that Uranus and Neptune, with lower temperatures than Saturn and Jupiter, have lost most of their class III materials must be due, at least in part, to lower original masses.

In summary, it is suggested that the bulk properties of a planet are determined by its critical molecular weight; that is, the weight of molecules whose escape time is equal to the lifetime of the solar system (Witting 1965). This is the simplest explanation of the difference between planets and it is consistent with all empirical data.

2.2 Atmospheres of the Major Planets

The spectra of the major planets present a problem which is entirely different from those presented by the spectra of Venus and Mars. It is much less a question of searching for bands of vanishing intensity than it is a question of identifying absorption bands of tremendous intensity in the red region of the spectrum.

The original work with photography on the spectra of the major planets was done over a long period of years by Slipher (1929). A band extending from 6450 to 6507 Å was the strongest observed and showed some evidence of structure. A considerable number of additional bands were also noted in the near infrared, extending to 8570 Å. In 1932, bands were observed beyond 9000 Å, including one at 10,150 Å.

At that time, detailed knowledge of the near infrared bands of the simple organic molecules was far from complete. It therefore seemed desirable to photograph the spectra of the planets with sufficient dispersion to permit measuring as many individual lines as possible, so as to provide a reliable basis for identification. Saturn was photographed in the 6400 Å region with a 15-foot Littrow prism spectrograph ($\approx$ 12 Å/mm). The ammonia observed, when compared with laboratory spectra, was apparently present at 2 m atm. Methane, with lines in the vicinity of 7200, 8000, and 8800 Å, was observed at a considerably higher concentration. That these compounds were detected does not necessarily mean that they are present as major constituents, however, since they are much more easily observed than H_2, He, etc.

Several faint spectra of Uranus were also obtained during this period, using a 7-inch camera with a plane grating, but the dispersion was not sufficient for a detailed study of the band structure. While work has continued during the years through to the present time, there are still very few details known about the atmospheres of these planets. In many cases even the vibrational assignment of many of the bands is uncertain. Any reported data, then, must be regarded as very approximate. No atmosphere has been detected on Pluto.

2.3 Interiors of the Major Planets

Various models of the major planets have been used for some time in attempting to describe the structure and composition of the planetary interiors. These models, making use of known and extrapolated chemical and physical properties of solids, can be developed assuming the presence of a certain chemical substance or mixture of substances. If a pressure-density relation is obtained which reflects the properties of the planet under investigation, and no other substance can yield such a relation, then a solution to the composition problem would be achieved (De Marcus 1959).

In the cases of the terrestrial planets such a program could not be carried out, since the densities could be matched by a variety of substances. In the cases of the two largest planets, however, the situation is far simpler since the densities as a function of pressure when calculated from any reasonable model cannot be matched by any substance which is not primarily hydrogen. From such work, the hydrogen content of Jupiter is estimated to be 80 percent by mass and that of Saturn about 60 percent by mass. The proportions of hydrogen in these planets are thus comparable with that in solar material. The internal density distribution in Jupiter and Saturn are then estimated on the assumption of chemical homogeneity. The proportion of heavier elements are chosen for each planet to agree with its empirical mean density. The computed moments of inertia of the planets are close to, but definitely larger than, the empirical values. This perhaps means that the heavier elements are not distributed uniformly in the planets but are to some extent centrally condensed.

The internal temperatures of these planets, while not known accurately at all at the present time, are generally felt to be low and not to appreciably affect the pressure-density relationship of the material in the planet's interior. Order of magnitude estimates for these temperatures are usually based on the assumption that the planet is neither heating up nor cooling down, and that the present temperatures are due either to radioactivity or to remnants of the planet's original heat when it was formed at stellar temperatures.

Upper limits for abundances of radioative elements are usually inferred from measurements on meteorites. Making appropriate modifications (Ramsey 1959), the rate of heating in the interior can then be estimated. Assumed values for thermal conductivity through the outer layers of the planet then lead to values for the temperature in the metallic cores of the planets of roughly 10,000°K.

The concept of attributing the present temperature to remnants of the planet's original heat was first examined by Jeffries (1938). He showed that since being formed, the planets have had time to cool by convection and that the temperature gradients are now no more than several degrees per kilometer. Such a procedure has been used by Ramsey (1951) and De Marcus (1957) to show that on this basis also the central temperatures are no greater than 10,000°K.

2.4 Satellites

At the present time, there are in all thirty-one known satellites of planets in our solar system (see Table 3). It is difficult to obtain much detailed information regarding these, however, due chiefly to their small sizes and the large distances involved. A tenth of a second of arc represents about a tenth of a mile at the distance of our moon, but at the distance of Neptune (30 AU) this is about 1350 miles. Thus our knowledge of the diameters of the satellites, or even of their positions with respect to the planet, is only approximate. In particular, it is almost impossible to detect the eccentricity of a nearly circular

Table 3

DATA ON THE SATELLITES OF SATURN, URANUS AND NEPTUNE

		Separation from Parent Planet at mean oppⁿ.dist. (10^3km)	'	"	Sidereal Period (days)	Synodic Period (days)	Inclination of Orbit to Planet's Equator		Eccentricity of mean Orbit	Magnitude at Mean Opposition Distance
Saturn										
I	Mimas	186		30	0.94242	0.943	1	31	0.0201	12.1
II	Enceladus	238		38	1.37022	1.370	0	01	0.00444	11.7
III	Tethys	295		48	1.88780	1.888	1	06	0	10.6
IV	Dione	378	1	01	2.73692	2.738	0	01	0.00221	10.7
V	Rhea	527	1	25	4.51750	4.519	0	21	0.00098	10.0
VI	Titan	1222	3	17	15.94545	15.969	0	20	0.0289	8.3
VII	Hyperion	1481	3	59	21.27666	21.319	0	26	0.104	15
VIII	Iapetus	3562	9	35	79.33082	79.920	14	43	0.02828	10.8
IX	Phoebe	12960	34	56	550.45	523.7	150		0.16326	14
Uranus										
V	Miranda	124		9	1.414	1.4	0		<0.01	17
I	Ariel	192		14	2.52038	2.521	0		0.0028	14
II	Umbriel	267		20	4.14418	4.145	0		0.0035	14
III	Titania	438		33	8.70588	8.708	0		0.0024	14
IV	Oberon	587		44	13.46326	13.469	0		0.0007	14
Neptune										
I	Triton	354		17	5.87683	5.877	159	57	0	14
II	Nereid	5570	4	24	359.4	362	27	27	0.76	19

orbit, and for the most part, the only orbital elements that can be measured with any accuracy are the longitude of the node and the inclination of the orbit. Table 3 gives data for the satellites of Saturn, Uranus, and Neptune.

Despite these limitations it is clear that satellites are of two particular kinds (Porter 1960). The first are the regular satellites, nineteen in all, which travel in almost circular orbits in the plane of the equator of the parent planet. The second are the twelve irregular satellites, whose orbits may be quite eccentric and inclined at any angle. In almost all cases the satellites are so close to the parent planet and so distant from the Sun and the other planets, that perturbations by these other bodies can be ignored. Mutual perturbations are, however, important in the case of the larger satellites, and this is particularly true of the four great moons of Jupiter and of the effect of Titan on the neighboring satellites of Saturn. In addition, the motion of close satellites is always modified by disturbances due to the oblateness of the parent planet.

Although it is unlikely that observations from early space missions would deal specifically with any particular planetary satellites, we can, for the sake of completeness, list those bodies associated with the major planets discussed here. The seven inner satellites of Saturn form a regular system with almost circular orbits lying close to the ring plane. With the exception of Titan, Saturn's satellites are much smaller than those of Jupiter, although they are closer to each other and to the planet. Mutual perturbations therefore occur, but they are not serious except in the case of

Rhea, which is nearest to Titan. An interesting feature here is that Titan is the only satellite on which an atmosphere has definitely been shown to exist. Two outer satellites complete the Saturnian system. The discovery of a tenth body, subsequently named Themis, was announced near the turn of the century, but its existence has never been confirmed.

Uranus has a system of five satellites, one of the most regular in the solar system. The only unusual thing here is that the planet's axis of rotation lies almost in the ecliptic plane so that Uranus appears to be laying on its side. This contrasts strangely with the positions of the axes of the other planets and suggests, according to Kuiper, that the Uranian system may have turned over some time in the past.

Neptune's two satellites, both irregular, afford a large contrast to those of Uranus. Further, Triton is one of six satellites in the solar system having retrograde motion (rotation in the sense opposite to planetary orbital and spin motion). The conditions are entirely different from those of the Uranian system, which led Kuiper to suggest that the satellite may once have escaped from Neptune with subsequent recapture. It is not at all clear, however, how this event could have taken place nor how recapture could give rise to a circular orbit.

Any satellites of Pluto, if they exist, have not yet been observed.

3. SATURN

3.1 Background

The Saturn planet-ring system was first observed and correctly explained in 1659 by Christiann Huygens, who also discovered the satellite Titan. Except for its ring system, Saturn is actually a smaller version of Jupiter, including some similar disk features. The most marked of these are the South Equatorial Belt and the North Tropical Belt, along with the darkish north and south polar regions. In addition, occasional markings include thin, streaky belts in high southern latitudes, and small white polar caps. All of these features are less well marked than those of Jupiter, and lack the coloring usually seen upon the nearer planet. They are probably due, however, to similar but unknown compounds of carbon, hydrogen and nitrogen.

During the course of disk observations, some rarely occurring spots have been noticed and used to evaluate the rotation period of the planet. These are white spots, due perhaps to rising currents of gas. Equatorial spots, some quite brilliant, were observed during the last century and as recently as 1933. Spots in higher latitudes are very rare. However, a great outburst of spots was observed in latitude 60° north in 1960 by Dollfus in France and Botham in South Africa. Rotational periods, as analyzed from these records by T. A. Cragg, were found to be 10 hours 30 minutes. This result seems to disagree with previous spectroscopic findings, which indicated that Saturn's rotation required an hour longer in latitude 57° than at the equator. Thus the complex motions of the planet's atmosphere are clearly not yet understood.

3.2 Atmosphere

Saturn appears generally much like Jupiter although our knowledge of its spectra is more limited due to its greater distance from the Earth. There is, in fact, some controversy existing regarding identification of certain spectral features. However, it appears fairly certain that NH_3, CH_4, and H_2 have been observed in the atmosphere and that the temperature in the regions of strongest absorption is in the range 90°K-100°K.

The Saturn CH_4 and NH_3 bands, just as those observed on Jupiter, appear as very strong features. The intensities are different, however, such that Saturn abundances are usually stated as 350 m atm for CH_4 and less than 2 m atm NH_3, using the intensities of bands in the 6000-9000 Å region and at 6450 Å respectively (Rea 1962). These contrast with Jupiter abundances for CH_4 of 150 m atm and for NH_3 of 7 m atm. Kuiper's 1952 near infrared data for Saturn show the same NH_3 and CH_4 bands as on Jupiter, but with the NH_3 much weaker. Moroz (1961), examining the infrared spectrum with a resolution of about 200 Å, observed an intensity greater than Kuiper's in the 1.65-1.8 and 2.0-2.3μ regions. This may be due to the relatively neutral reflection spectrum of the rings superimposed on the disk spectrum, or perhaps to greater apparatus sensitivity. At any rate, an abundance of 10-15 cm atm of NH_3

was estimated using these data. This number is much smaller than the original estimate, but even more surprising is the fact that no NH_3 lines were found on excellent high dispersion spectrograms taken for just that purpose in 1962 (Spinrad 1964). It appears, then, that some observations have been unreliable or that the NH_3 abundance on Saturn is variable.

Molecular hydrogen is the other atmospheric constituent which has thus far been identified. Both the S(1) and S(0) lines of the (4,0) band were observed by Spinrad, leading to an abundance estimate of 40 km atm H_2. This is not far from the value computed assuming solar composition.

Murray and Wildey (1963), using the 8-14μ infrared window of our atmosphere, report that they were unable to detect any signal from Saturn and thus set an upper limit for the temperature at 105°K. This can be compared with a rotational temperature of 88°K obtained from the H_2 spectra, and an 8-14μ temperature of 128°K reported by Menzel, Coblentz, and Lampland (1926). The discrepancy between the two infrared values is significant enough to justify further radiometer work on Saturn using telescopes larger than the 19" instrument employed by Murray and Wildey.

The only quantitative study of the absorption across Saturn's disk was made by Hess (1953) when the rings were edge-on to the Earth. The CH_4 band at 6190 Å exhibited a marked increase in equivalent width toward the poles, this being accepted despite the large errors due to difficulties in determining the latitude on Saturn at which the spectrographic slit was placed. Interpretation is difficult, however, since scattering through a hazy atmosphere could alter any estimates made for relative atmospheric heights.

Finally, it might be mentioned that with the slit aligned along the equator, the CH_4 lines are inclined so that the methane appears to be rotating about 10 percent faster than the cloud layer producing the scattered Fraunhofer spectrum (Munch and Spinrad 1962). This is exactly opposite to the case for Jupiter, where the line inclinations were less than if the gas rotated with the planet and is in contrast to the H_2 lines, which suggest that the hydrogen is apparently moving with the same rotational velocity as the planet.

3.3 Interior

The interior of Saturn presents about the same problem as the interior of Jupiter. There is general agreement that any planet larger than Neptune must possess large quantities of hydrogen and helium if its density is to be in the range 0.7 to 1.4 g/cm^3. There is also thought to be present a much smaller amount of heavy, earthlike materials.

The internal constitution of Saturn has been investigated on the basis of the atomic theory of solids. The starting-point of such a study is the theoretical pressure-density relationship for solid hydrogen at absolute zero temperature; the internal temperature of the planet can be shown to be too low to influence the density appreciably.

The hydrogen abundance is generally believed to be 60-65 percent by mass, the heavy elements probably no more than a few percent, with the remainder helium. According to De Marcus (1957), it appears that the insensitivity of the hydrogen abundance to changes of various assumptions gives every indication that future improvements are not likely to lead to abundance estimates which are very different than the present ones.

In constructing models for Saturn, the equation of state of hydrogen was used to relate the pressure and density in the outer layers of the planet. The equation of hydrostatic equilibrium was integrated inward from the surface to a point where the model was completed by placing a dense core in the center. Having fixed the details of this core, the ellipticity was calculated, and always turned out to be somewhat larger than the ellipticity of Saturn.

This difference may be due to the uncertainty in the rotational period, since the discrepancy between ellipticities is only about 10 percent and could be removed by altering the rotational period within reasonable limits. It may also be due to errors in the extrapolated equation of state of hydrogen which was used in these calculations. De Marcus (1957) made some improvements with an alternative equation of state, but still noted minor discrepancies. It thus appears that the derivation of a model which exactly reproduces the internal features of Saturn does not seem possible on the basis of present knowledge and that it is doubtful if anything additional will be settled before more detailed observations are made from at least a fly-by mission.

3.4 Saturn's Rings

The rings of Saturn were first seen in 1610 by Galileo, but their nature was not determined until 1656 when Huygens discerned that the planet was surrounded by a circular ring that was very flat and was not connected to the planet. In the 1670's Cassini found the ring was double, a dark line separating it into two concentric rings. The dark line is called Cassini's division, the outer ring A, and the inner ring B. In 1850 Bond at Harvard and Davies in England independently discovered a very tenuous third ring, a "crape ring" or ring C, inside the first two. Other divisions of the main rings have been described from time to time. Generally, though, these are just circles of lesser intensity rather than an actual division. The most conspicuous such division is in ring A and is called Encke's division.

Until celestial mechanics was adequately developed, many astronomers thought Saturn's rings to be continuous bands. Maxwell, in 1859, was the first to show that a liquid or solid ring could not survive rotating around a planet, but that a ring composed of a multitude of small bodies would be stable so long as the total mass of the small bodies was small compared to the planet. This theoretical deduction may be verified by observation, since it suggests that the more remote particles have to orbit more slowly than the nearer ones. Keeler, measuring velocities by means of the Doppler shift of spectral lines, demonstrated that the ring was indeed composed of many bodies by showing it was in differential rotation, the inner part moving faster than the outer part. Each particle then making up the ring travels around Saturn almost as if it were all alone in a Keplerian orbit.

The outer diameter of ring A is 272,500 km, the inner diameter 239,900 km. The outer diameter of ring B is 234,200 km, the inner diameter 181,300 km. The inner diameter of ring C is 148,100 km. It appears that the rings are very thin, for if they were many particles thick damping by collisions would reduce that thickness to effectively one particle in less than a year. It is estimated that the largest particles may be several meters in size but that the average size is much smaller. The fine inside ring is apparently composed of a predominantly fine dust (Barabashov 1964). The gaps in the rings are apparently due to perturbations caused by Saturn's satellites. This is a resonance effect, whereby ring particles having periods of revolution related to the periods of the inner satellites are soon forced into different orbits.

Kuiper has suggested that the particles making up the ring system are either covered by frost or composed of ice on the basis of the low reflectivity of the ring near 1.5μ. Recent work by Frederick (1963) and Owen (1965a) in the region 10,400-10,900 Å has substantiated this suggestion. The observation of this second absorption makes it virtually certain that the absorbing substance associated with the ring particles is water ice. The absorption observed by Kuiper at 1.5μ is the solid-state equivalent of the ψ vapor band at 1.38μ. The second absorption corresponds to the ρ vapor band at 0.93μ. Thus the situation apparently corresponds to a true solid state absorption and not an evaporation effect, since in the latter case, one would only expect to see the low temperature rotational lines in the vapor band at 0.93μ.

That ice can persist under conditions of high vacuum is clear from its vapor pressure, which is about 1.5×10^{-19}μ Hg at 90°K. This implies that the largest ice particles which could evaporate since the origin of the solar system are only slightly larger than a water molecule. The same argument may be used to exclude ices of methane and ammonia, since their vapor pressures are too high.

Further detailed information concerning the rings may be obtained during the occultation of stars by the rings. The occultation of bright stars is exceedingly rare, occurring less than once a century. However, occultations of stars of stellar magnitude 7 to 8 occur more than once a decade, so that professional observations in the near future could yield additional information on the optical thickness and distribution of matter in the rings.

3.5 Radio Emission

Detection of 3.45 cm radiation from Saturn was achieved (Cook et al. 1960) with an X-band ruby maser radiometer installed on the 85 ft University of Michigan antenna. The initial detection came from seven drift curves, the average indicating a peak antenna temperature of about 0.1°K. This value indicates an equivalent black body disk temperature of roughly 110°K, neglecting the effect of radiation from the rings. This is in fair agreement with optical measurements and with the infrared data of Murray and Wildey.

Later, work was done at the National Radio Astronomy Observatory (Drake 1962) using a 10 cm traveling wave tube radiometer. The mean value of the black body temperature was 196°K, when it was assumed the rings did not contribute to the observed emission.

Combining the data obtained at the two wavelengths, and assuming that the flux density S follows the law

$$S = K\nu^x ,$$

where K is a constant and ν is the frequency, a value of $x = 1.4$ is obtained. It is thus possible that the spectrum is not that of a black body (for which $x = 2$).

One interpretation is, of course, that the radiation is of thermal origin, but that the emission at the two wavelengths arises from different depths of an atmosphere with a temperature gradient. A second interpretation can be made by assuming observations of atmospheric levels of the same temperature at 3 and 10 cm. Then, about 100°K of brightness temperature at 10 cm is of nonthermal origin. In any case, the absolute nonthermal radio luminosity of Saturn appears to be less than about 1/6 that of Jupiter at centimeter wavelengths. This is not surprising, since it has often been assumed that the rings of Saturn tend to capture any radiation belt particles, preventing the existence of a dense belt system.

That there is a belt of at least some magnitude, however, is suggested by the linear polarization of 10 cm emission recently detected by Zheleznyakov (1965). This has been attributed to synchrotron radiation of relativistic electrons. The polarization plane appears to be close to the axis of rotation so that the magnetic field (with a dipole oriented along the rotational axis) must be considerably deformed in the region of the radiation source (estimated to be at a distance of the order of one planetary radius from the surface). The magnetic lines of force could be nearly parallel to the equator (and not perpendicular to it as at lower altitudes) due to the differential character of the plasma rotation in the planet's exosphere. This character of rotation may possibly be related to the entrainment of plasma by the particles making up the rings.

4. URANUS AND NEPTUNE

4.1 Background

The planets, out to and including Saturn, have been known to man since time immemorial and it apparently did not occur to anyone, during the early period of advancing modern astronomy, that any others might exist. Thus Uranus was discovered inadvertently in 1781 by William Herschel while in the process of a complete sky survey. As a result of the impossibility of reconciling predicted and observed positions of Uranus, Adams in England, and Leverrier in France independently predicted that a new planet would be found in the constellation of Aquarius; thus, the planet Neptune was found in 1846.

Both planets have tremendous quantities of methane, although no measurement for their mean molecular atmospheric weight is yet available. Some tentative work by Kuiper suggests very faint cloud belts on Uranus, but both planets appear so small in a telescope that no permanent markings have ever been observed. Uranus may exhibit peculiar climatic effects because of its orientation. Since this planet's axis is fixed nearly in the ecliptic plane, the angle which it makes with respect to a line joining the Sun and the planet varies throughout its orbit. Thus conditions vary from a situation where only one hemisphere receives energy from the Sun to the other, familiar case where the Sun rises and sets once each Uranian day.

4.2 Atmosphere (spectra)

The absorption bands in the visible spectrum of these planets have been interpreted as due to 2.2 and 3.7 km atm of CH_4 on Uranus and Neptune, respectively. The huge methane bands completely alter the appearance of the continuous spectrum of Uranus from the yellow to the infrared, and may conceal weaker bands of other molecules. No NH_3 has been observed on either planet; it is probably frozen out, as is CO_2 and H_2O.

A most interesting feature of the spectra of these planets is the presence of several broad absorption lines in the red and near-infrared which are most likely due to normally forbidden transitions in the H_2 molecule. An intense line at 8267 Å was observed first, with a width of about 30 Å. Herzberg reasoned that what was being observed was actually a transition of the H_2 dipole spectrum induced by pressure effects. He then photographed the spectrum of H_2 at a pressure of 100 atm and a temperature of 78°K, and observed five lines in the vicinity of 8250 Å, each approximately 40 Å wide. The wavelength of the S(0) line of the 3,0 band was found to be 8250 Å, somewhat lower than the Uranus line measured by Kuiper at 8267 Å, and later by Herzberg himself at 8260 Å. Herzberg regards the differences in these numbers as due to psychological effects in finding the center of a broad line, and believes the assignment of the Uranus line to H_2 to be reasonably certain. If the Uranus 2 Å shift is real, it may be due to the different molecules inducing the absorption (Rea 1962).

An interesting contrast between the Uranus and laboratory spectra is the apparent absence of a line at 8166 Å despite the fact that in the laboratory a line here has an intensity greater than the 8258 Å line. The line is a super-position of the S(1) line of the 3-0 band and of the Q(0), Q(1) combination of the (2,0)(1,0) band. Its weakening could be due to a lower percentage of the H_2-H_2 collisions. From the half-width of the Uranus S(0) line Herzberg estimates the temperature to be close to that for the laboratory spectra (i.e., about 78°K) so that the diminution in the intensity of the 8166 Å line must be due primarily to dilution by a foreign gas. In view of the density of the planet this is considered to be He with a He:H_2 ratio of 3:1. This latter is only a crude number and probably only represents a lower limit for the ratio.

The intensity of the S(0) Uranus line, from a visual comparison with laboratory plates, is equivalent to 120 m at 100 atm. For a 3:1 abundance ratio of He and H_2 this corresponds to 127 km atm of H_2 and 378 km of He with a total pressure of 8 m at the bottom of the reflecting layer. These numbers are rather uncertain at the present time, but the techniques are reliable and further work should improve these estimates.

Two additional interesting features in the spectrum of Uranus were found at 7500 Å and 7524 Å, with subsequent spectra adding a third at 7471 Å. Neptune was found to exhibit these same bands, and the presence of a feature at 7546 Å in the spectrum of Neptune confirmed its presence in the Uranus spectrum. Laboratory spectra of many gases were investigated in an attempt at identification, but all failed to account for the observed features. Finally, Owen (1965b) was led to reconsider the possibility that they might in fact be due to CH_4. Using an effective path length of over 5000 m atm, good agreement was found between the laboratory and Uranus spectra, with the exception of a Uranus feature at 7481 Å. Thus it appears likely that methane is responsible for almost all the hitherto unidentified absorptions.

4.3 Interior

The relatively good agreement which has been reached regarding the composition of Jupiter and Saturn is due primarily to the fact that no element or substance has properties which can be confused with hydrogen, the chief constituent of those planets. The maximum weight fractions of hydrogen on Uranus and Neptune, on the other hand, are estimated at only 0.23 and 0.14, respectively (De Marcus and Reynolds 1962). This predominance of material other than hydrogen within Uranus and Neptune as well as the relative lack of observational data precludes the possibility of obtaining a well-defined solution to the compositional problem at the present time.

In constructing models for Uranus and Neptune, Reynolds and Summers (1965) have used estimates for the relative abundances of the constituent elements provided by Aller (1961). Chemical equilibrium of the Aller mixture at the low temperatures characterizing the outer regions of the solar system results in silicon and magnesium being present in the form of oxides. The remaining oxygen, as well as the carbon, nitrogen, and sulfur, exist in the form of hydrides. Iron and nickel are considered to remain in the uncombined state.

Two approximations can rather naturally be made for these planets. First, the strength of the material composing these bodies is greatly exceeded by the effect of the internal pressures at all depths below a negligibly small distance from the surface, so that the equation of hydrostatic equilibrium can be employed. Second, for solid bodies having the masses and dimensions characteristic of the outer planets and having central temperatures of the order of 10,000°K or less, the effects of temperature will be completely overridden by pressure effects. With these assumptions, the pressure-density relation and the Clairaut equation for the ellipticity can be solved using an equation of state for each of the constituents. These are approximate and a number of extrapolations and interpolations must be performed. However, the equations do provide reasonable and consistent estimates and permit the calculation of models for Uranus and Neptune.

The results indicate the composition of these planets must lie somewhere between that of a pure hydrogen-helium-neon mixture and that of a planet composed entirely of nonvolatile materials. The difference in mean density of the two planets is primarily dependent on the relative amounts of the light elements retained by the two bodies. A comparison of values obtained from the models shows that the fraction of hydrogen-helium-neon retained by Uranus is 2.7 times the fraction retained by Neptune. The internal density distribution preferred for Neptune indicates a moderate degree of internal condensation with the formation of a large, relatively homogeneous core. The models obtained for both planets then are composed primarily of an ice (ammonia, methane, hydrogen sulfide and argon) mixture with about one-half their mass being H_2O and a small fraction of the rock mixture (oxides of silicon, magnesium and iron).

5. PLUTO

Pluto was discovered in 1930 by Clyde Tombaugh as a result of a deliberate photographic search initiated years before. The search was begun as early as 1905 as the result of calculations by Percival Lowell predicting the existence of another planet as well as an approximate location for it. There was considerable surprise, however, due to the fact that it was found to be a small terrestrial type planet.

This fact, plus the extreme eccentricity of its orbit, immediately brought up the question of the planet's origin. There has been particular interest in this problem since it is considered improbable that Pluto could have originated at the same time and under the same conditions as the other planets. It is generally felt that two distinct planets with near intersecting orbits (such as those of Pluto and Neptune) could not have formed during the solar system evolution, but rather that a single planet would have resulted (Kuiper 1956a). Further, it could not be as large as it is if accumulated by means of accretion. The satellite origin theory is the obvious alternative, although Kuiper does not feel that an encounter with Triton has any part in the release. He and Rabe have presented considerable evidence that Pluto was released from

Neptune as this planet lost mass during its period of evolution.

Kuiper also pointed out that if Pluto originated as a satellite of Neptune, slow rotation would be expected, comparable to its original period of revolution. Walker and Hardie (1955) were able to measure the rotational period of Pluto photometrically in 1955. The result gave a period of rotation of 6.4 days, a completely reasonable value.

Few other facts are known about Pluto aside from its orbital elements. Kuiper (1950) made a direct determination of the diameter of Pluto using a disk meter. This is a telescopic attachment designed to produce a small artificial luminous disk of controllable brightness, color, and diameter which can be compared with the astronomical body being studied. The value obtained was 0.46 times the diameter of the Earth, or about 5860 km. This is in good agreement with a recent observation by Halliday et al. (1965), who, during a near occultation of a 15th magnitude star, estimated an upper limit to the linear diameter of Pluto as 6400 km. If the density of Pluto does not exceed that of the Earth then the corresponding upper limit to the mass of Pluto would be 0.13 Earth masses. If, on the other hand, the current value of 0.92 Earth masses were adopted for the mass of Pluto, the lower limit for Pluto's mean density would be 50 g/cm^3, an incredibly high value for a small body where degeneracy cannot set in.

It is estimated that the maximum temperature on Pluto may be about 70°K, with the average temperature about 50°K. Most species would freeze out of Pluto's thin atmosphere, the bulk of which is probably made up of neon and argon. In fact, as far as can be told, Pluto is practically a twin to Triton physically.

6. BASIC SCIENTIFIC QUESTIONS

There are many scientific questions which can be asked at present concerning any and all characteristics of the outer planets. However, it must be kept in mind that, with the exception of Pluto, we are concerned with conditions such that most of the information to be obtained from a simple flyby or orbiting mission will be primarily related to the outer layers of a very extensive, optically thick atmosphere. Because of this situation, early missions should be devoted largely to resolving questions raised by recent Earth-based observations and to generally completing the descriptions of these atmospheres and planetary exteriors. Attention may then be turned in subsequent, more sophisticated missions to problems directly related to planetary surfaces and interiors.

Some of the more pertinent questions which are in keeping with such a goal are given below.

1. What is the species concentration and distribution within the atmospheres? In particular, what is the NH_3 content on Saturn (or is it variable) and what is the H_2-He ratio on Uranus and Neptune?
2. What is the structure of the belts, spots, and other features which have been observed on Saturn?
3. What is the mean molecular weight of the atmospheres of Uranus and Neptune?
4. What is the origin of the "nonthermal" radio noise from Saturn?
5. What is the magnitude and configuration of the planetary magnetic fields?

6. Do ionospheric and auroral effects exist for any of the planets?

7. What is the temperature distribution and energy balance throughout the atmospheres and bodies of the planets?

8. What is the exact nature of the particles in the Saturnian ring system and what is the mass of the system?

9. What is the true rotational period of Saturn?

10. What are the best models for the planets' interiors?

11. What is the mass and diameter of Pluto?

7. BASIC MEASUREMENTS AND EXPERIMENTS

The primary goal of early missions to the outer planets must be to contribute to the description of the origin of the solar system, and the subsequent events, that led to the arrangement of terrestrial and major planets as they are today. The field for experimentation by space probes is thus almost limitless. There are certain experiments, however, and certain kinds of information which would be more natural than others to consider for an early mission. They might well be chosen from among the following.

7.1 Magnetometry

The first outer planet mission should obviously include the capability for magnetic field measurements in the range 10^{-6} to 10 gauss. Two instruments will be required, one with a lower limit near 10^{-6} gauss for interplanetary field measurements and the other with an upper limit near 10 gauss for planetary field measurements.

7.2 High-Resolution IR Spectroscopy

A vast amount of spectroscopic data are needed to answer the countless number of questions regarding the planetary atmospheres. First of all, species identification, concentration, and distribution within the atmospheres must be better understood. Aside from contributing to knowledge of the interiors, the answers to these questions relate to the radiation balance in the atmosphere and the structure of belts, spots, or features which are as yet unexplained. Several other detailed investigations are:

a) Determination of NH_3 content on Saturn.

b) Atmospheric temperature determination for Uranus using the broadening of H_2 lines.

c) Auroral and airglow emission spectra to determine ionospheric properties for any of the planets.

d) Search for complex organic molecules.

e) H_2-He ratio on Uranus and Neptune.

7.3 Visible and UV Spectroscopy and Polarimetry

Spectroscopic examination of the planetary atmospheres in the visible and UV spectra should yield additional information regarding constituents, pressure, temperature and spatial distribution of materials. In addition, attempts at identification of additional compounds is important in constructing reliable atmospheric and planetary models.

Polarimetry studies might be used to determine the amounts of Rayleigh and Mie scattering and thus yield information concerning cloud cover, particulate matter in suspension, and structure of the atmosphere. The extension of phase angle coverage as compared to Earth-based observations will be of special significance for this work.

7.4 Radiometry

On a close approach to a planet it becomes possible to obtain spatially resolved information using microwave receivers. Thus it is feasible to:

a) Use cm-wavelength observations to measure the magnitude and regions of emission on the three outermost major planets.

b) Determine the origin of the nonthermal noise on Saturn.

c) Use active radar probing to determine such things as actual distance to the planetary surface, true rotation periods, etc. This, however, may require power in excess of that available on early missions.

7.5 Vehicle Motion

Data from an orbiter can provide improved values for gravitational parameters.

7.6 Occultation Experiments

Several experiments of this general type can be performed. Among them are:

a) Occultation of the Sun or a star by Uranus and/or Neptune for determination of atmospheric mean molecular weight.

b) Occultation by Saturn's rings for determination of optical thickness and distribution of matter.

c) Occultation of the vehicle signal around the planetary atmospheres for density determinations.

7.7 Photography

Photography must be considered as a tool of investigation, since data with high resolution will be of interest when considering cloud structure and surface features. The information bandwidth required is very large, however, so that during preliminary surveys it may be likely that other experiments will give more knowledge for a given transmitting capacity.

7.8 Atmospheric Penetration

It might be feasible to plan for part of the payload to enter the planetary atmosphere, where it may "float" like a bathyscape or at least return information to the orbiting vehicle before it crashes. Such things as radio transmission through the atmosphere, mass spectroscopy, and chemical tests for bio-molecules might be considered here.

7.9 Pluto Mass and Diameter

An approximate value for the planet diameter is apparently the only physical knowledge of Pluto in existence at the present time. An important first step might thus be to determine the mass of the planet by observing the effect of its gravitational field upon the motion of the space vehicle. It is also possible to determine the diameter much more accurately, either by positioning the vehicle so as to cause an occultation of a star by the planet, or by a direct optical observation using an on-board telescope.

7.10 Earth-Based Observations

Because of the great distances to the outer planets, most additional detailed knowledge must await the flight of a space vehicle. There is, however, a limited number of experiments which can be performed from Earth during the coming years. Among these are (1) professional observation of 7th or 8th magnitude star occultations by Saturn's rings for improved optical thickness and distribution determinations, and (2) large telescope, 8-13μ radiometry observations of Saturn for improved temperature measurements.

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